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DISCLAIMER

DESIGN CONSIDERATIONS, TOOLING, AND EQUIPMENT FOR REMOTE IN-SERVICE INSPECTION OF RADIOACTIVE PIPING AND PRESSURE-VESSEL SYSTEMS

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MASTER

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ABSTRACT

In-Service Inspection programs are performed to monitor and verify the integrity of a nuclear power plant's primary pressure boundaries. Early detection of abnormal structural or material degradation could preclude serious damage to plant systems.

This paper summarizes results obtained in use of remotely-operated nondestructive testing (NDT) equipment for inspection of reactor-system components. Experience obtained in operating the Fast Flux Test Facility (FFTF) has provided a basis for field verification of remote NDT equipment designs and has suggested development improvements.

Remote Viewing and data gathering systems used include periscopes, borescopes, fiberscopes, hybrid borescopes/fiberscopes, and closed circuit television. A summary of design consideration for inspection equipment and power plant design is presented to achieve improved equipment operation and reduction of plant maintenance downtime.

INTRODUCTION

Development of specialized inspection tooling and equipment is necessary to meet the In-Service Inspection (ISI) requirements of highly radioactive piping and pressure vessel systems, such as those found in fast breeder reactors. These nondestructive testing (NDT) systems provide the capability to remotely inspect hazardous inspection areas and gather data accurately and expeditiously.

The following types of equipment systems have been employed for remote In-Service Inspection of fast breeder reactor ASME coded components:

- Periscopes
- Borescopes
- Fiberoptics
- Hybrid Borescope/Fiberscope Systems
- Closed-Circuit Television

These systems have been used or demonstrated for remote NDT inspection of reactor components in areas of inaccessible or restricted access during normal plant outages.

This paper addresses the gathering of data and experience gained through the use of these systems at the Fast Flux Test Facility (FFTF) near Richland, Washington. Specific areas discussed are:

1. Remote inspection system design, description and application.
2. Plant design considerations to augment and expedite inspection activities.
3. Summary of design considerations for NDT equipment designers and operators for enhancement of remotely operated NDT equipment.

INSPECTION REQUIREMENTS AND METHODS

Inspection Requirements

Inspection and data acquisition requirements for coded vessels and components must be clearly defined prior to beginning equipment design. The techniques and technology to be used for meeting the requirements must be reviewed and approved by the responsible user organizations. Substantial costs and outage schedule impacts may be incurred by designing inspection equipment that either far exceeds or falls short of requirements for performing the required inspection.

Inspection Method

Inspection equipment designers must clearly define what method is to be employed to meet the specified inspection requirements. First, it must be determined in advance of system design how the inspection data are to be acquired and documented. Two broadly defined methods are employed with remote inspection equipment: the Hard Copy Method and the Subjective Method.

1. Hard Copy Method - This method produces a permanent inspection record, such as a photograph, videotape, or computer storage. This method provides for an objective evaluation of the inspection data. The hard copy results can be compared to a set of baseline standards to determine whether there has been progression of crack growth or other degradation. Several persons may study the records to provide a consensus of opinions. Eye fatigue and other sensor biases are reduced.

2. Subjective Method - In this method, a qualified inspector is responsible for making an immediate decision based on what he/she "sees." The inspector must rely on memory for any comparative evaluations. This method renders standardization of inspection results impracticable. Inspection validity depends entirely on one person's visual acuity, competence, and interpolation. For these reasons, the consistency of accuracy is lower than evaluations utilizing the hard copy method.

Defining early in the plant and inspection equipment design process which of the above methods is to be used for inspection data gathering will provide for more cost effective inspection equipment and fewer iterations in the design/development of the inspection system.

TOOLING AND EQUIPMENT FOR REMOTE IN-SERVICE INSPECTION USE

Remote Viewing Equipment

Periscopes. Periscopes have been employed at the FFTF for visual weld inspection on ASME primary system piping and components.

ISI periscopes are employed for data acquisition in the following areas:

- Monitoring Heat Transport System (HTS) cell piping and component motions due to thermal expansion and mechanical vibrations.
- Visual weld inspection on critical piping and piping support systems.
- Location and verification of gross leaks.

127 mm (5-in.) Diameter Periscope. The 127 mm (5-in.) diameter periscope is a high-resolution, dual magnification instrument. It is used for viewing piping, piping supports and other components in the HTS cells that are normally inaccessible during plant outages.

The periscope assembly (Figure 1) consists of three main categories of components.

1. The eyepiece box containing optics and instrument operating controls.
2. Relay extenders, for varying the operating length of the periscope.
3. The viewing head, which contains the high and low power objective lenses, variable-power viewing light, and scanning viewing mirror.

The periscope can be extended, with the addition of up to six relay extenders, to a total length of 15.2 m (50 ft). It can be used with any number of relays to provide a working length from 1.22 m (4 ft) to 15.2 m (50 ft), in increments of 2.25 m (89 in.). The periscope is designed to operate in an environment of 232°C (450°F) maximum temperature, at an internal pressure of 82.6 kPa (12 psig), and absorb gamma radiation to levels of 10^8 Rad.

A motorized magnification power shift feature within the periscope enables the operator to select low or high power viewing. The "power shift" operation is performed by mechanical control rods extendings from a motor drive in the eyepiece box, through the relay sections, to the objective lenses in the viewing head. The periscope's motorized scanning mirror is similarly arranged.

Viewing illumination is provided by a light mounted in the periscope head.. The light angle is remotely positioned independent of the viewing mirror. This design feature enhances inspection area illumination during operation. A position readout device for the light has been included in the periscope controls to enable reproducible lighting conditions during repeat inspection activities.

Photographic illumination is provided by a 1200 watt-sec electronic strobe, fixed-angle mounted in the periscope head. The strobe enables short-duration flash photographs to be taken during inspection and data gathering operations. Sufficient light is provided to allow use of high-speed black and white, and ASA 400 color film.

Field use of the periscope has shown that flash photographs yield excellent inspection data and allow photographic enhancement techniques to be employed if further data resolution is required. Additionally, the strobe unit eliminates photograph blurring caused by facility vibration or periscope motion. Such blurring has been a significant problem with time exposed photography techniques.

The periscope optical system is capable of spatial resolutions of 5 arc seconds for the high power objective and 25 arc seconds for the low power objective. This translates into resolutions of .025 mm (0.001 in.) at 1 m (3 ft) for the high power objective and 0.25 mm (.01 in.) at 2 m (6 ft) for the low power objective. The periscope's motorized viewing mirror can remotely scan ±45° from the horizontal line of sight. The viewing mirror is equipped with angle indicator marks etched on the mirror window. This enables expedient repositioning of the viewing mirror during repeat or verification inspection activities. The optical lens system in the periscope is fabricated of non-browning, cerium-stabilized glass to prevent lens degradation in a high-radiation field.

The periscope eyepiece, relay extenders and head sections are connected by means of threaded coupling rings. Alignment during component assembly/disassembly is assured by an externally visible key/slot arrangement mated with an internal dowel pin. This provides alignment guidance during the assembly operation to minimize possible damage to the electrical connectors, power shift and scan control rods located within the 5-in. diameter of the periscope cross section.

The use of the 5-in. periscope at FFTF has yielded considerable experience regarding mechanical design. The periscope components are rugged and durable, necessary factors for any piece of equipment used in "field" applications. The 6.35 mm (1/4-in.) diameter control rods for the power shift and scanning operations are of sufficient size and coupling design to allow easy assembly of the periscope components with minimal possibility of damage.

Electrical connections are made by a "plug-in-socket" arrangement. The periscope component alignment guides are crucial to avoid electrical plug and socket damage during the assembly operation. The external and internal keying arrangements in the eyepiece and in each relay and head section have provided sufficient alignment that no electrical connectors or insulators have been damaged during inspection operations at FFTF.

A 76.2 mm (3-in.) diameter periscope is also utilized for inspection of specific smaller diameter, guard vessel penetrations (see Figure 2). The 76.2 mm periscope shares many of the same features of the 127 mm (5-in.) diameter unit.

The Appendix provides a general checklist of design considerations to be used when designing or specifying ISI periscopes.

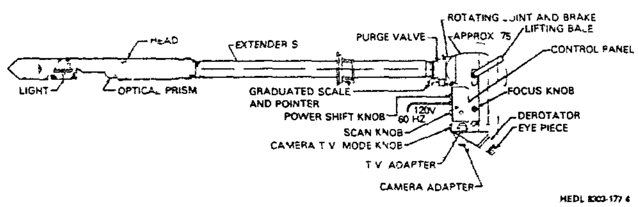

FIGURE 1. 127 MM (5-INCH) DIAMETER PERISCOPE

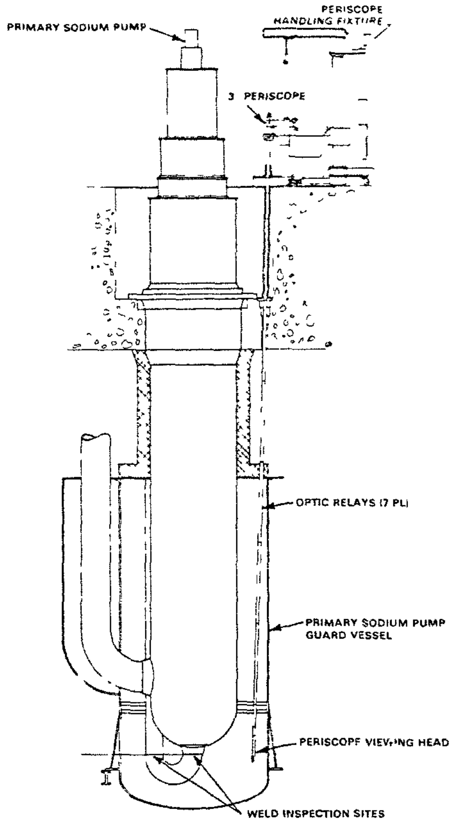

FIGURE 2. 76.2 MM (3 IN.) DIAMETER PERISCOPE ARRANGEMENT FOR PRIMARY SODIUM PUMP GUARD VESSEL INSPECTION

Borescopes. A borescope inspection system has been employed at FFTF to conduct visual surveys of damaged components and to support subsequent repair activities. This inspection system has been specially designed to operate at ambient temperatures of 204°C (400°F) and inspect components with inside diameters as small as 25.4 mm (1 in.).

The borescope system is used for inspections requiring high resolution and hard copy documentation. The borescope system (Figure 3) consists of the following features:

1. Eyepiece assembly, containing viewing ports for simultaneous attachment and use of high-power eyepiece, low-power eyepiece, CCTV camera, and 35 mm camera. Additionally, the eyepiece assembly provides for image derotation and viewing light intensity control.

2. Relay assemblies, consisting of optical relays of 23.8 mm (15/16 in.) diameter variable to 44.5 mm (1-3/4 in.) diameter. The relays allow for extension of the borescope to 7.3 m (24 ft) in 1.2 m (4 ft) increments.

3. Viewing heads, including a panoramic and a right angle viewing head, each containing a 100-watt viewing light.

Excellent results have been obtained in use of the borescope inspection system. Its relative ease of deployment and capability for multimode viewing makes it a versatile inspection system. It enhances general plant inspection activities and minimizes plant downtime when remote visual inspection of small-diameter components is required.

The Appendix provides a checklist of general design considerations to be used when specifying borescopes for inspection applications.

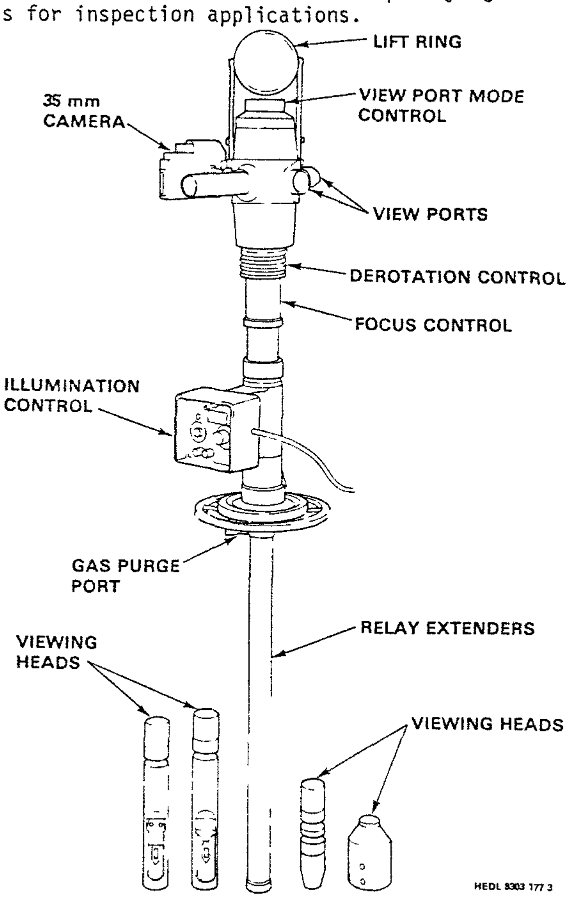

FIGURE 3. HIGH TEMPERATURE BORESCOPE

Fiberscope Inspection Systems

Fiberscopes are flexible instruments that are normally used when no straight line entry port is available, or if it is necessary to inspect around corners, as within curved tubing or pipe.

The fiberscope image guide carries the image gathered at the objective lens back to the eyepiece. Some fiberscopes have a controllable bending section near the tip so the observer can direct the scope during insertion and be able to scan an area of interest.

Standard industrial fiberscopes containing lead silicate core fibers or polymer-clad silica (PCS) with a T08 natural fused quartz core are susceptible to radiation damage. Total doses of 1000 rads will render these systems useless by blackening the fibers.(1) In comparison, fiberscopes containing PCS fibers drawn from synthetic pure fused silica have a lower sensitivity to radiation damage and are usable to total doses of 10^6 rads.(1)

(1) Friebele, E.J., Jaeger, R.E., Sigel, G.H. and Gingerich, M.E., "Effect of Ionizing Radiation on Optical Attenuation in Polymer-Clad Silica Fiber-Optic Wave Guides," Appl. Phys. Lett., Vol. 32 No. 2, 1/15/78.

Due to the relative high cost of standard industrial fiberscopes, limited working lengths, and susceptibility to radiation damage, they have not been applied as regular ISI devices at FFTF. Instead, periscopes, borescopes or CCTV cameras have been employed.

A hybrid fiberscope/borescope inspection system was designed and demonstrated for potential application in the damaged Three Mile Island reactor plant (see Figure 4). The system incorporates a radiation-resistant, 6 m (20 ft) long borescope and a commercial grade, 4.6 m (15 ft) long, fiberscope. The fiberscope was coupled at the objective end of the borescope. Various lenses and an illumination package attached to the objective end of the fiberscope produced the desired viewing results. A CCTV camera and video recording unit attached to the borescope eyepiece recorded the inspection.

The inspection system was designed for deployment through a ventilation shaft containing a right angle bend approximately 6 m (20 ft) from the access area (Figure 5). The site to be inspected was approximately 3.6 m (12 ft) from the bend in the vent shaft. The hybrid borescope/fiberscope system yielded excellent inspection results. Although optical resolution of the total system was somewhat reduced by the coupling of individual components, the system was capable of the necessary resolution for a general evaluation survey

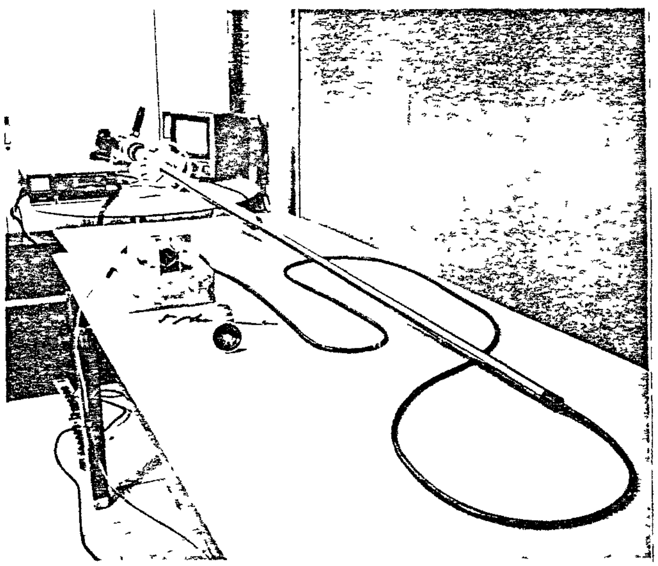

FIGURE 4. HYBRID BORESCOPE/FIBERSCOPE SYSTEMS

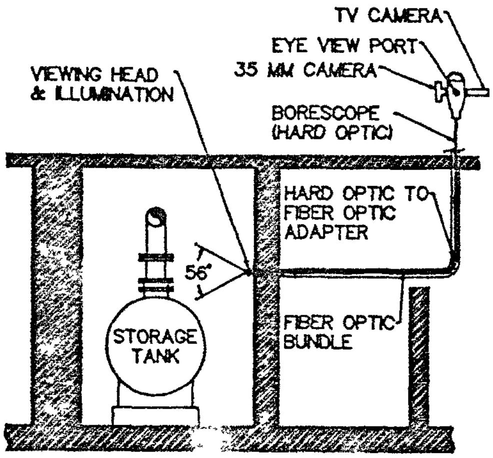

FIGURE 5. HYBRID BORESCOPE/FIBERSCOPE ARRANGEMENT FOR INSPECTION OF A REACTOR COOLANT DRAIN TANK

CCTV Camera Systems

Several different types of remotely controlled CCTV camera systems have been employed for visual inspection of reactor and related system components. These cameras have been used with various types of deployment systems such as extendable, pole-mounted cameras, Figures 6 and 7, to systems employing a small remote controlled CCTV camera for viewing around the outside surface of sodium filled vessels. In all the developed systems, similar types of low-light-level, black and white, high-resolution, radiation hardened vidicon cameras were employed.

Use of CCTV for component inspection at FFTF has yielded important information relative to the design and implementation of illumination, optical lenses, and camera umbilical cabling.

CCTV Illumination

In most remote inspection installations, illumination must be carried with the camera in the deployment mechanism. FFTF field experience has shown best success with variable-intensity, quartz halogen lights that are remotely positionable independent of camera viewing angle. Best results were also obtained when the camera was equipped with remote iris control. These features afforded the maximum flexibility in viewing illumination and provided excellent inspection data.

Illumination "quantity" was determined experimentally for the specific system application. Design considerations for the camera deployment mechanisms allowed for additional lighting space as demanded by differing inspection situations.

Optical Lens. Camera lenses should be evaluated and selected to meet the requirements of the specific inspection task. It is often necessary to use a wide angle lens (12.5 mm) for general survey purposes. This lens offers a 52° x 39° field of view. This enhances the ability to locate the specific inspection areas to be surveyed. Use of ultra-wide angle or fish eye lenses (5.5 mm) may yield a visually distorted view of the inspection area. Depending upon the inspection requirements, this visual distortion may be acceptable.

Selection of high focal length lenses (25 mm) provides excellent close-up inspection results but can make location of the specific inspection site difficult.

Use of lenses with remote iris and focus control provides added flexibility to the inspection camera and expedites inspection activities.

Camera Umbilical Cable. The CCTV Camera inspection systems used at FFTF required special umbilical cabling, incorporating camera control and signal wiring, deployment equipment control wiring and electrical power wiring. Radio Frequency (RF) shielding is an important feature in order to eliminate RF "noise" caused by adjacent wiring or plant equipment, which can distort camera output signals and reduce video resolution.

Considerations should be given to environmental parameters (i.e., temperature, radiation, atmosphere, etc.) in design of the cable. The cable should have a smooth and highly durable exterior. Incorporation of Kevlar material into the cable for physical reinforcement and abrasion resistance produced good field results.

ADVANCED REACTOR PLANT DESIGN CONSIDERATIONS FOR USE OF REMOTE NDT INSPECTION EQUIPMENT

Advanced nuclear power plants must be designed for accommodation of ISI capability as a key criterion to minimize inspection time and outage downtime costs. Plant inspection requirements must be addressed beginning with initial plant layout studies. If inspection equipment considerations are not addressed until later in the design phases, inspection operations will be adversely affected by lack of adequate NDT equipment space, work access, crane utility and other requirements for efficient inspections.

Advanced sodium-cooled reactors present unique problems relative to inspection requirements due in part to the coolant properties of the plant. Inherent to an advanced sodium-cooled reactor plant are high ambient temperatures, 204°C (400°F), during normal plant shutdown and residual radiation due to corrosion products deposited on the inner walls of pipe and equipment in the primary sodium system. These factors must be considered when providing access for remotely operated inspection equipment.

The following criteria should be considered in advanced reactor plant design to assure adequate ISI capability:

1. Identify areas of high component stress and select areas to be examined periodically for long-term changes in material conditions. The means of inspection (whether contact or remote) and the specific NDT test applicable (radiograph, visual, or other) must be selected.

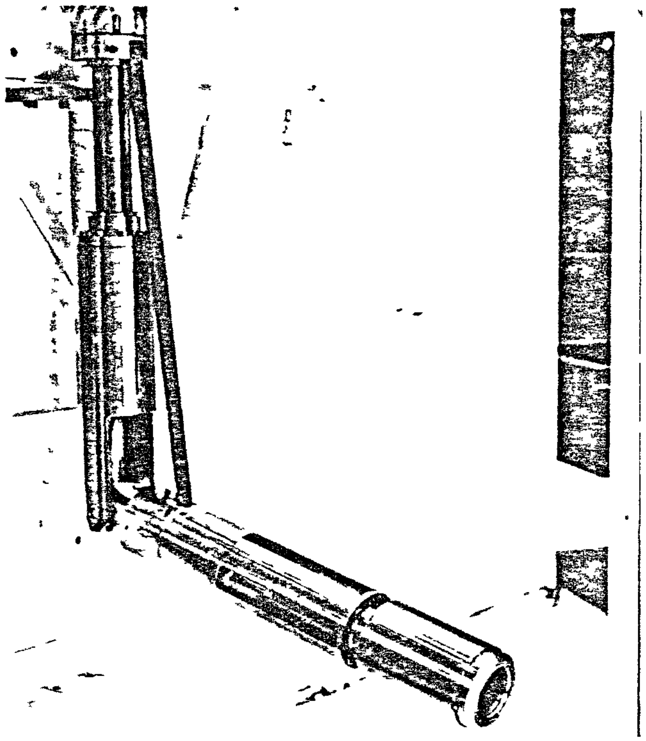

FIGURE 6. REMOTELY DEPLOYABLE, POLE MOUNTED CCTV INSPECTION SYSTEM

INTERIM DECAY STORAGE (IDS)

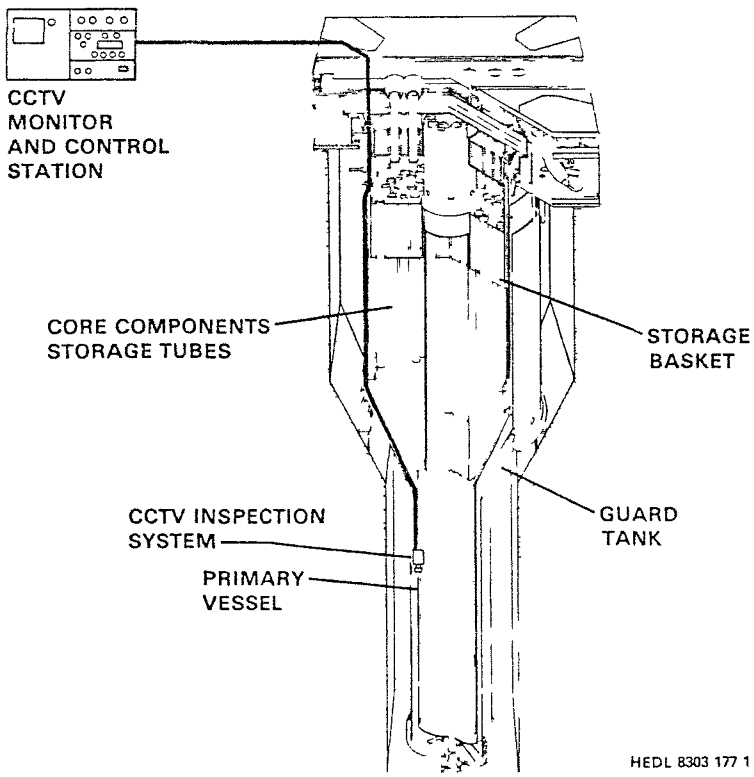

FIGURE 7 ARRANGEMENT FOR CCTV INSPECTION OF INTERIM DECAY STORAGE VESSEL

Check design of the weld or other features being inspected for compatibility with the test selected.

2. Provide access routes, ladders, work platforms, temporary or permanent shadow shielding, lighting, power, and communications to work sites for in-service inspection. Provide remotely movable insulation packages at the examination location.

3. Provide hoists, hatches, or other in-cell equipment to handle or remove structural components, insulating blocks or other items in the course of ISI procedures.

4. When remote ISI procedures are mandatory, provisions must be made in design for entry and positioning of the examination equipment and for remote movement of the insulation. Compatibility of the inspection equipment with the expected radiation flux must be included in the considerations.

5. Provide the largest inspection equipment access possible for the deployment of remote NDT equipment components. The smaller the access, the more costly the inspection equipment and the more susceptible to handling and operational damage.

6. Provide a means of illuminating the inspection surface for possible direct visual monitoring during conduction of the inspection. This may include special access way for auxiliary viewing lighting. Lighting should be 270 to 325 lux (25 to 30 footcandles) minimum at the inspection surface.

7. Means must be provided for cleaning the surfaces to be inspected, either before or after the inspection.

8. Make pre-service measurements of the areas or features to be monitored during future plant inspections to establish a base from which to judge changes in condition. These measurements should, if at all possible, be made with the actual inspection equipment and in the same manner as subsequent measurements to assure compatibility.

9. Make use of accurate plant mockups for personnel training and to assure required components can be inspected.

10. Limit the need for remotely operated auxiliary equipment to open inspection access ways.

11. Coordinate plant design and inspection access design with cognizant inspection equipment engineering personnel to assure plant system compatibility.

APPENDIX

CHECKLIST FOR DESIGN OR SPECIFICATION OF A REMOTE VIEWING SYSTEM

The following checklist should be used to aid in determining design and operational parameters for remote inspection system periscopes, borescopes, fiberoptics and CCTV systems.

1.0 <u>Viewing Application</u>

1.1 Observer Location - Determine the location of the observer relative to the objective end of the viewing device in both distance and plane.

1.2 Focus Range - Determine the distance from the objective end of the viewing device to the subject to be viewed. Determine whether this is a variable or fixed distance.

1.3 Subject to be Viewed - Determine the smallest detail size to be viewed at the focus range distance. Determine information regarding the subject's color, surface finish and contrast relative to its surrounding environment.

1.4 Total Areas to be Viewed - Determine the area to be viewed at a specified distance from the objective end of the viewing device. Specify whether the viewing area is to be scanned and in what plane (horizontal or vertical).

1.5 Physical Interfaces - Determine the physical interfaces of the viewing system. This includes penetration diameters, potential obstructions to viewing and system deployment, human/electronic and human/optical interfaces, facility vibrations, deployment equipment, etc.

1.6 Environment - Define environmental parameters for system operation. Specify atmospheric temperature and pressure ranges, define consistency (i.e., air, inert gas, moisture content, vacuum). Outline available illumination in lux or watts -- including present backscatter and attenuation coefficients.

1.7 Radiation - Determine radiation exposure and total dosage system is to absorb in Rads. Highlight any special shielding requirements necessary to protect operators during assembly/disassembly and use of the system.

1.8 Viewing Mode - Determine the viewing mode for the system: direct viewing, CCTV, combination viewing, still photography, high-speed motion picture, etc.

2.0 Optical Performance

2.1 Resolution - Determine the smallest subject that is to be viewed at the specified viewing distance. For optical instruments, resolution is specified in degrees of arc. In CCTV systems, resolution is determined by lines of video output.

2.2 Contrast - Although difficult to determine, contrast can have a significant effect on resolution. Contrast is expressed as the ratio between variations in densities or shades of grey.

2.3 Exposure Time (optical systems) - Determine the speed at which photographs are to be taken. Exposure times in excess of 1/30 sec frequently result in degraded photographs due to internal and external system vibrations. Strobe illumination should be considered when limited viewing lignt is available.

2.4 Magnification - This is the ratio between the angle of view seen by the operator through the inspection system (apparent field) and the actual angle or field of view seen by the system (true field). A magnification range of 2x (low magnification) to 10x (high magnification) is generally suitable for most inspection applications. Viewing systems should be capable of magnification changes without removal of the system from the inspection site.

3.0 Viewer Requirements

3.1 Par Focality - This system feature allows the operator to divert the optical image after focusing in the direct viewing mode and automatically be guaranteed of focus in the other viewing modes (i.e., CCTV or photographic).

3.2 Image Rotation - This feature allows the operator to retain the image in an erect position in those applications where the inspection instrument or subject rotates.

3.3 System Sealing or Purging - It is important to ensure that optical sections of the viewing system are sealed and backfilled with dry nitrogen or purged with dry gas during system use to prevent fogging and internal condensation of the lens system.

3.4 Scan Capability - Determine scan angle requirements for viewing. This may consist of movement of a scanning mirror or movement of the inspection system in a horizontal or vertical plane. Specify if scan angle is to be indicated by use of index marks or electronic readout devices.

3.5 Internal System Illumination - Determine the amount of light required to satisfactorily operate and meet inspection requirements. For maximum viewing flexibility, the lighting intensity should be adjustable. Optimum illumination would be 270 to 540 lux (25 to 50 footcandles) at the surface of the subject. The manipulation of the light should be independent of the optical positioning components.

3.6 Human Factors - Determine operator/system interfaces for both inspection equipment and auxiliary deployment equipment. Applicable sections of MIL-S-1472B (Human Factors in Equipment Design) should be used whenever possible. A comprehensive training program should be developed to instruct personnel in the use of the inspection equipment. Inspection personnel should be trained and qualified using the identical equipment and conditions to be found under actual field operations.

3.7 Auxiliary Support and Deployment Equipment - Determine the requirements for handling equipment to be used in support of the inspection system. Handling equipment should be quickly and easily assembled and disassembled. Human factors should be considered in the design. The equipment should be designed to provide necessary electric power, purge gas, thermal cooling, personnel shielding, deployment indexing and mobility as necessary to support the inspection operation. The auxiliary support equipment should require minimal services from the plant to support inspection operations.